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Flutter-Enhanced Mixing: Flow-Induced Flutter of Flexible Membranes in Small Scale Mixers

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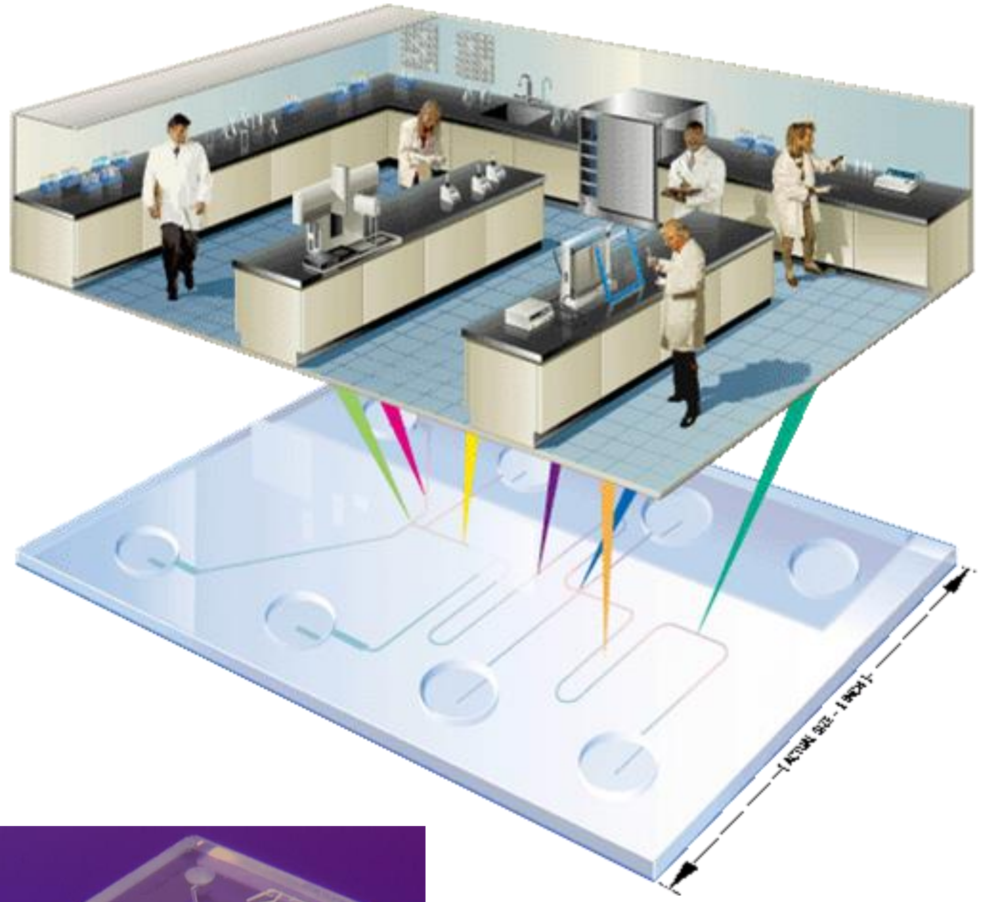
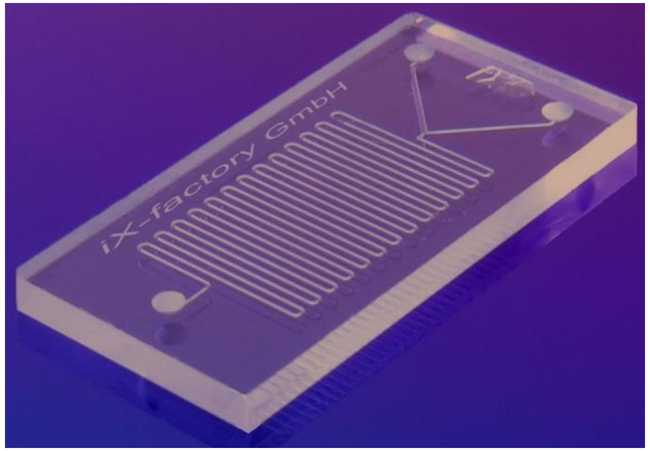
F P C L Flow Physics & Computation Lab

Mixing Enhancement: Motivation

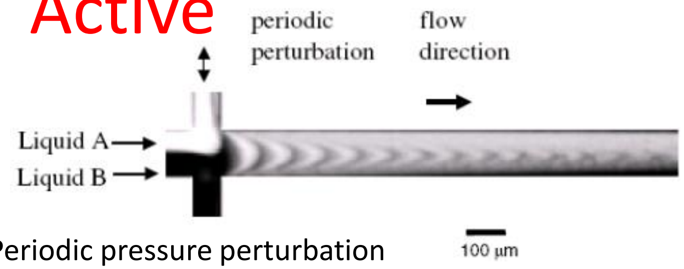
- Many low Re mixing applications such as lab-on-chip technology
- Microfluidic systems have many advantages over conventional approaches
- Inertial Microfluidics: (1<Re<100)
- Mixers usually classified as either active or passive mixers





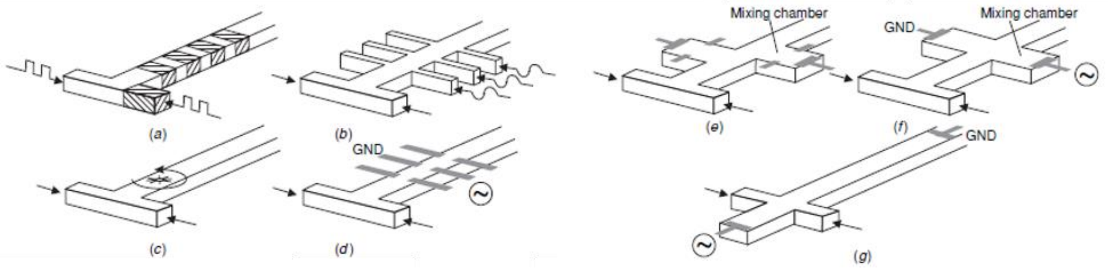
Mixing Enhancement:
Active vs. Passive Mixing

Active



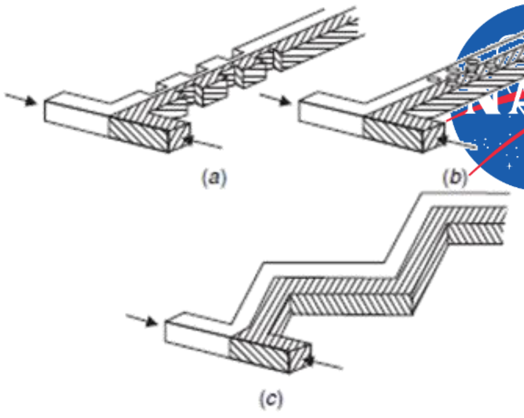
Periodic pressure perturbation design (Niu & Lee 2003)

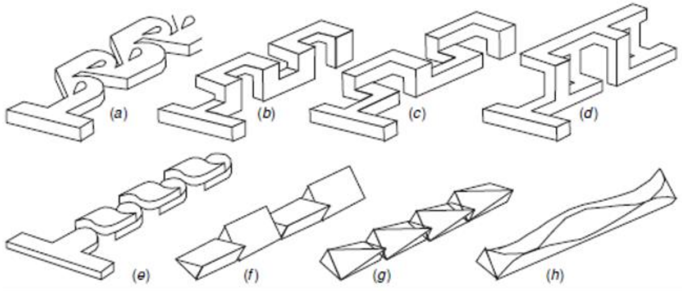
- Many Approaches
- Good performance
- Complicated implementation

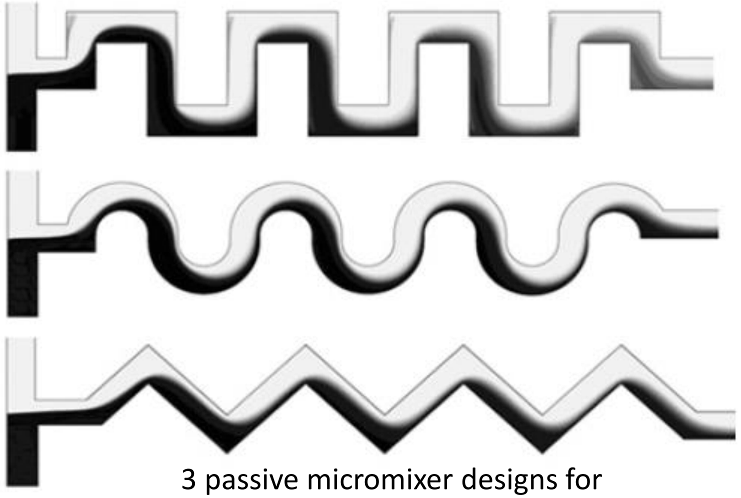


Passive

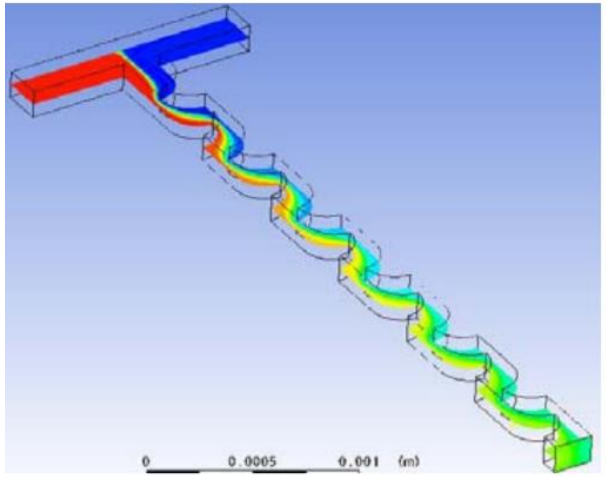
- Inertial range allows for chaotic advection
- Typically poorer performance
- Simpler implementation







3 passive micromixer designs for inertial mixing (Hossain et. Al. 2009)



Flow Induced Flutter (FIF)




- Flexible bodies immersed in a flow can undergo self excited aeroelastic flutter
- Flow induced vibration/flutter is ubiquitous in natural and engineered systems
- FIF is often a nuisance and even a failure mode
- However, we can take advantage of these phenomena

Governing Equations

Coupled Fluid – Structure – Scalar governing equations

Mass:
$$\nabla \cdot \mathbf{u} = 0$$

Momentum:
$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\nabla p + \frac{1}{Re}\nabla^2 \mathbf{u} + \mathbf{f}$$

Incompressible Navier-Stokes on collocated* cartesian grids

Position:
$$m_s \frac{\partial^2 \mathbf{X}}{\partial t^2} = \frac{\partial}{\partial s}(\sigma\boldsymbol{\tau} + \gamma\mathbf{n}) - \mathbf{F}$$

Tension:
$$\frac{\partial^2}{\partial s^2}(\sigma\boldsymbol{\tau}) \cdot \boldsymbol{\tau} = \frac{m_s}{2}\frac{\partial^2}{\partial t^2}(\boldsymbol{\tau} \cdot \boldsymbol{\tau}) - m_s \frac{\partial \boldsymbol{\tau}}{\partial t} \cdot \frac{\partial \boldsymbol{\tau}}{\partial t} - \frac{\partial}{\partial s}\left(\frac{\partial(\gamma\mathbf{n})}{\partial s} - \mathbf{F}\right);\ \gamma = \frac{\partial}{\partial s}\left(k_b \frac{\partial^2 \boldsymbol{X}}{\partial s^2}\right) \cdot \boldsymbol{n}$$

Zero thickness, elastic beam, inextensible (2D only)

Scalar:
$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \frac{1}{\mathrm{Re} \cdot \mathrm{Sc}}\nabla^2 T + \boldsymbol{q}$$

Scalar Advection-Diffusion

Non-dimensional Parameters

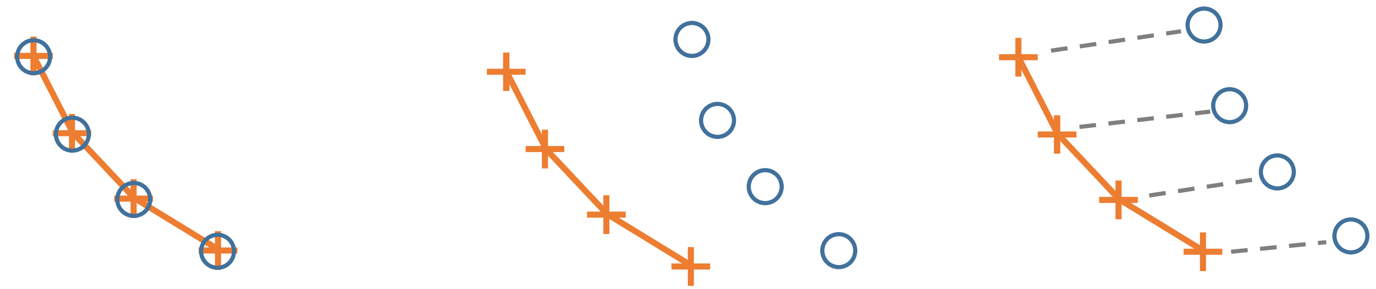
$$\mathrm{Re} = \frac{\mathrm{UL}}{\nu}$$

$$U^* = UL\sqrt{\frac{m_s}{k_b}}$$

$$M^* = \frac{\rho L}{m_s}$$

$$\mathrm{Sc} = \frac{\nu}{D}$$

FSI Penalty Method Coupling



$$\boldsymbol{u}^n, \boldsymbol{P}^n \quad \boldsymbol{X}^n, \boldsymbol{U}^n \;\longrightarrow\; \widetilde{\boldsymbol{X}}_{ib}^{n+1}, \boldsymbol{U}_{ib}^n \;\longrightarrow\; \mathbf{f}^n \quad \mathbf{F}^n$$

Fluid Solver $\longrightarrow$ $\boldsymbol{u}^{n+1}$, $\boldsymbol{P}^{n+1}$

Structure Solver $\longrightarrow$ $\boldsymbol{X}^{n+1}$, $\boldsymbol{U}^{n+1}$

Calculate new virtual particle position

Calculate penalty force

$$\widetilde{\boldsymbol{X}}_{ib}^{n+1} = \boldsymbol{X}_{ib}^n + \boldsymbol{U}_{ib}^n \Delta t$$

$$\boldsymbol{U}_{ib}^n = \int_{\Omega_F} \boldsymbol{u}^n(\boldsymbol{x})\, \delta\left[\boldsymbol{x} - \widetilde{\boldsymbol{X}}_{ib}^{n+1}\right] d\mathbf{x}$$

$$\mathbf{F}^n = -K_p \frac{\rho U^2}{L}\left[\left(\widetilde{\boldsymbol{X}}_{ib}^{n+1} - \boldsymbol{X}^n\right) + \beta \Delta t \left(\boldsymbol{U}_{ib}^n - \boldsymbol{U}^n\right)\right]$$

$$\mathbf{f}^n(\mathbf{x}) = \int_{\Gamma} \mathbf{F}^n(s)\, \delta[\boldsymbol{x} - \boldsymbol{X}^n(s)]\, ds$$

Note: Other bodies modeled using a sharp interface immersed boundary approach

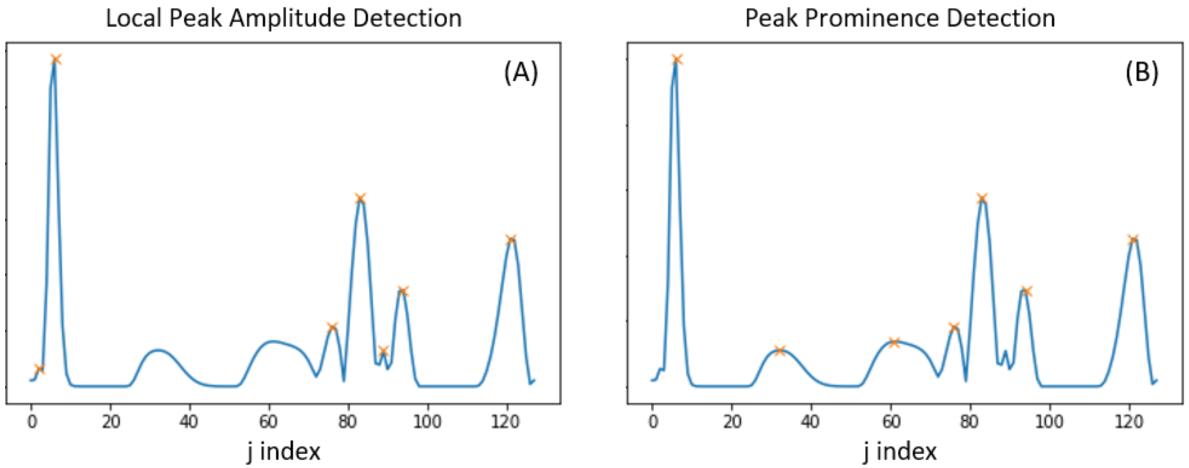
K_p and β are large, negative penalty parameters

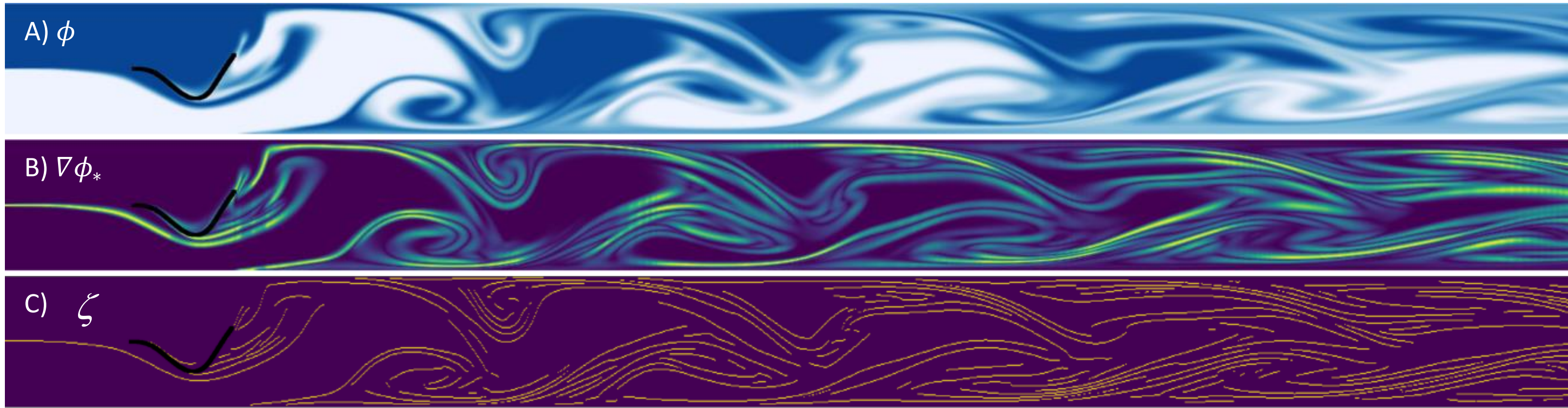
Mixing Enhancement: 2D Performance Measures

- Head loss (HL)
  - $\mathrm{H}(x) = \int_0^H \left(P + \frac{1}{2}u^2\right) dy$
  - $\mathrm{HL}(x) = \mathrm{H}(0) - \mathrm{H}(x)$
  - Measures energy expended since the inlet

- Mixing Index (M)
  - $\sigma = \sqrt{\frac{1}{H}\int_0^H (T - \bar{T}_m)^2 dy}$
  - $M = 1 - \sqrt{\frac{\sigma^2}{\sigma_m^2}}$
  - M ranges from 0 to 1
    - 0 is unmixed flow (T = 0 or 1)
    - 1 is mixed flow (T = 0.5)

- Interface Density (I_D)
  - Calculate Normalized Gradient:
  - $\nabla\phi_*(x,y) = \frac{\nabla\phi(x,y)}{\|\nabla\phi(x)\|_\infty}$
  - Find peaks of $\nabla\phi_*(x,y)$ using peak prominence to make ζ field
  - Average of ζ at each x is I_D





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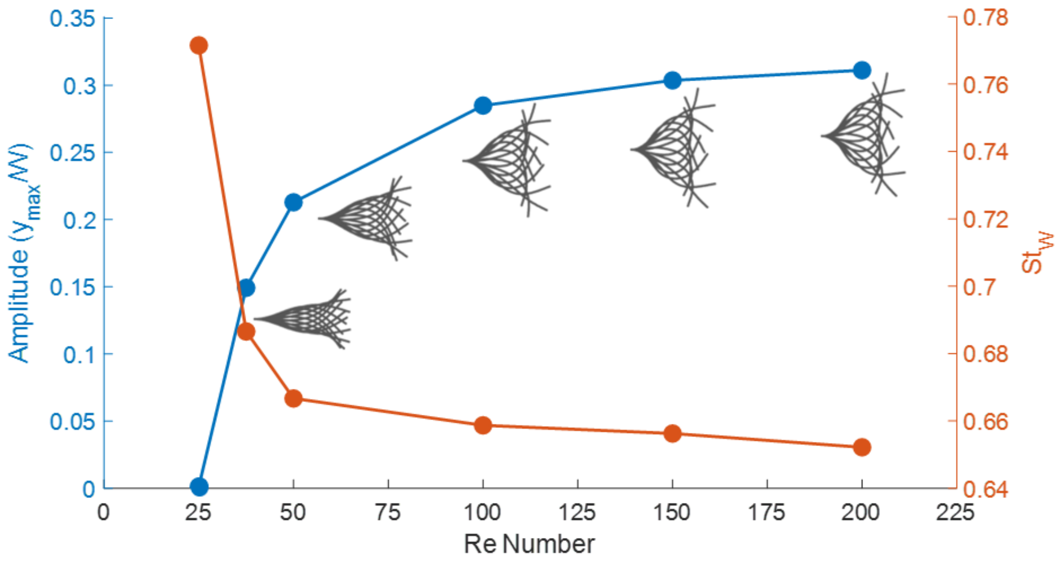
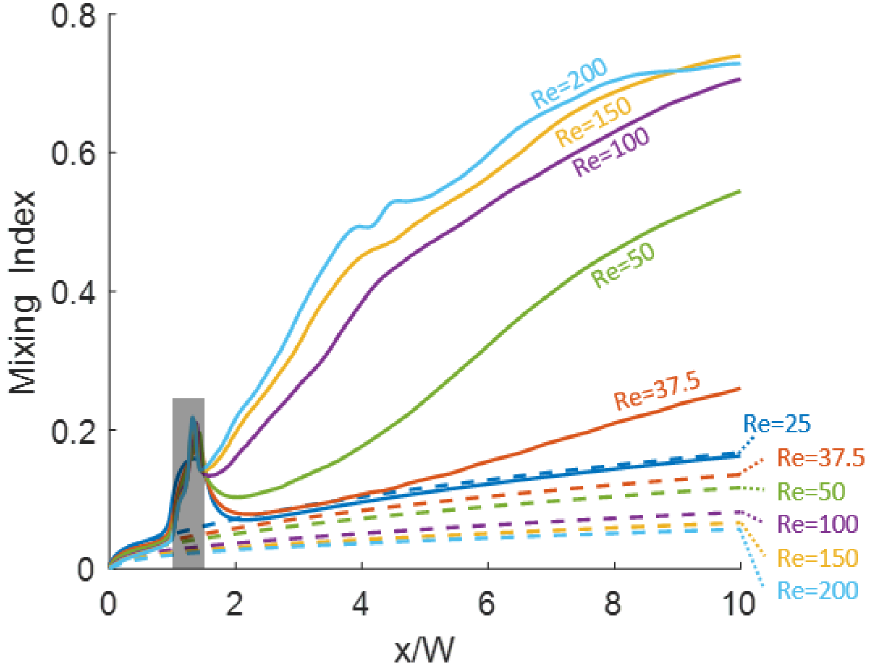
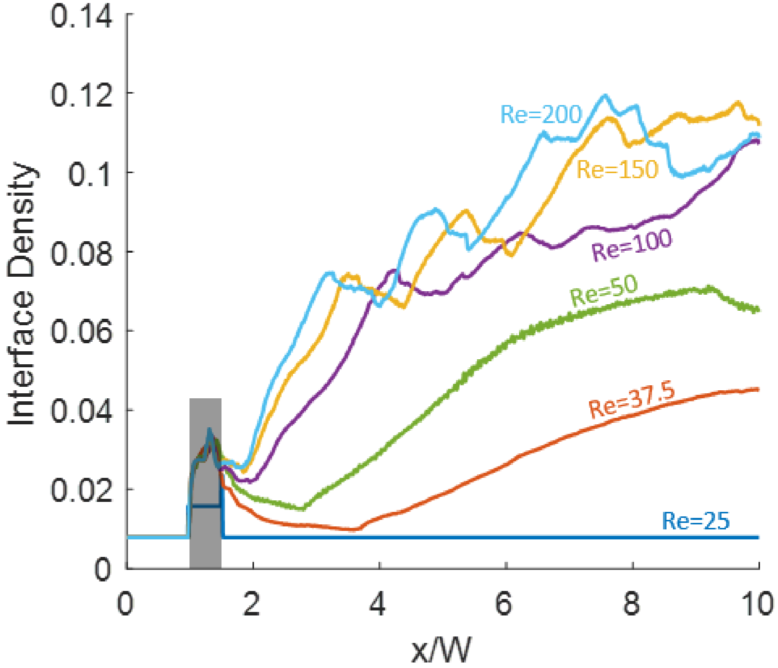
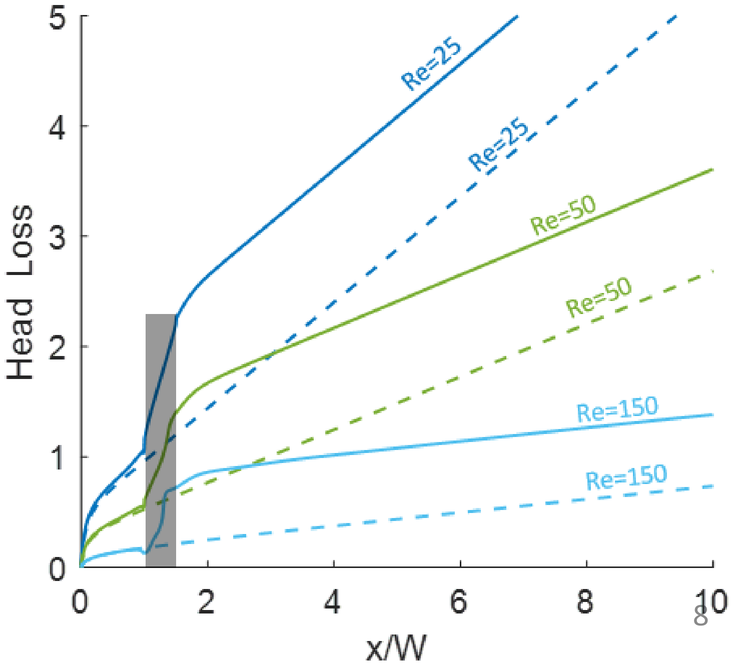
Effect of Reynolds Number



- Behavior progression: onset, transition, saturation
- Interface Density lags Mixing Index
- Nonmonotonicity in Interface Density is likely a 2D artifact
- One time Head Loss penalty due to flag







Problem Description

Governing Equations:

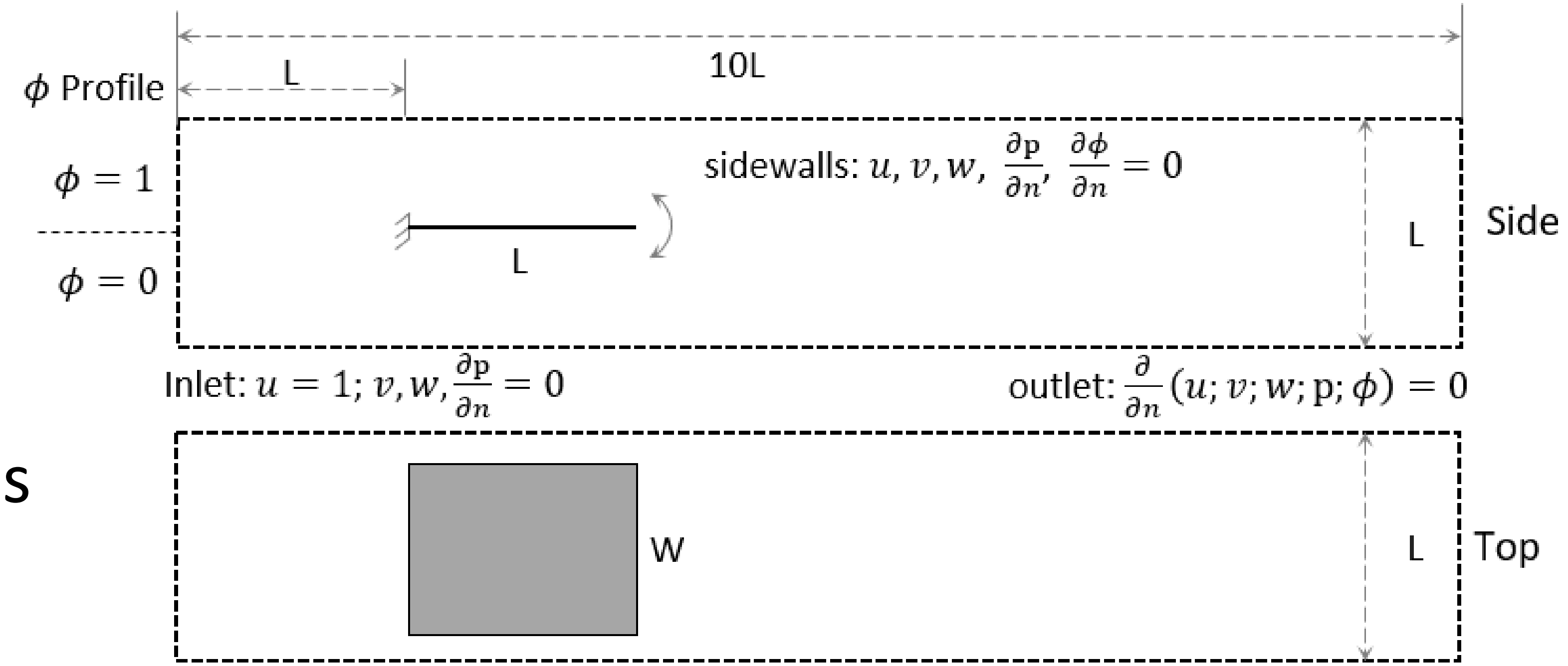
$$\frac{\partial \mathbf{u}}{\partial t}+\nabla\cdot(\mathbf{uu})=-\nabla p+\frac{1}{\mathrm{Re}}\nabla^2\mathbf{u}+\mathbf{f}$$

$$\nabla\cdot\mathbf{u}=0$$

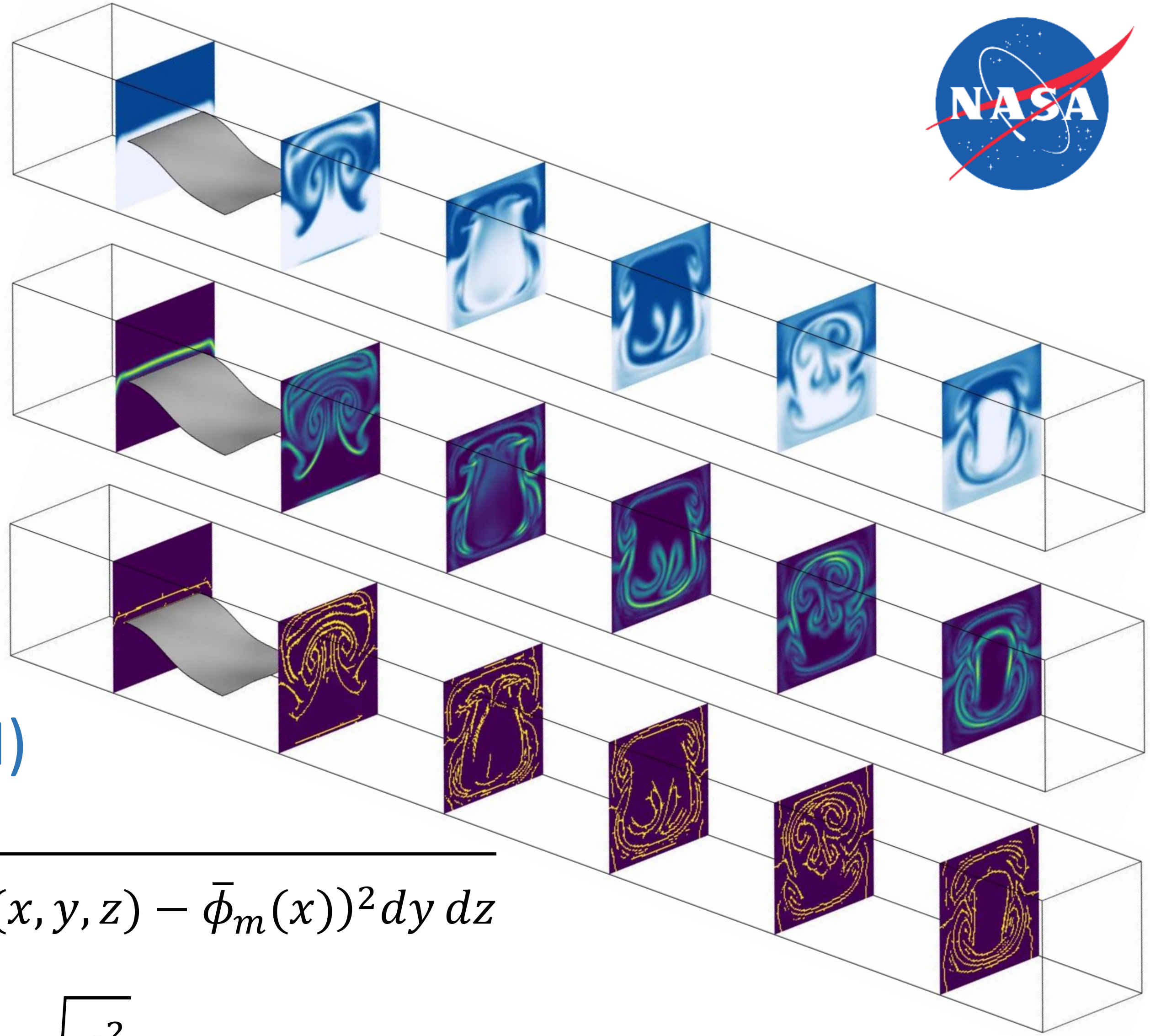
$$\frac{\partial T}{\partial t}+\mathbf{u}\cdot\nabla T=\frac{1}{\mathrm{Re}\cdot\mathrm{Pr}}\nabla^2 T$$

$$\frac{\partial^2\mathbf{X}}{\partial t^2}=\sum_{i,j=1}^{2}\left[\frac{\partial}{\partial s_i}\left(\sigma_{ij}\frac{\partial\mathbf{X}}{\partial s_j}\right)-\frac{\partial^2}{\partial s_i\partial s_j}\left(\frac{M^*}{U^{*2}}\frac{\partial^2\mathbf{X}}{\partial s_i\partial s_j}\right)\right]+Fr\frac{\mathbf{g}}{g}-\mathbf{F}$$

- Re = 50-200; Sc = 100
- dx_f=0.015L; 960x96x96
- dx_s=0.0125L; 120 pts/L
- dt = 0.0001; 10^6 time steps



Performance Measures



Head loss (HL)

$$\mathrm{H}^*(x) = \frac{1}{\rho U^2}\int_0^Z \int_0^Y \left(P + \frac{1}{2}u^2\right) dy\, dz$$

$$\mathrm{HL}(x) = \mathrm{H}^*(0) - \mathrm{H}^*(x)$$

Interface Density (I_D)

$$\nabla\phi_*(x,y,z) = \frac{\nabla\phi(x,y,z)}{\|\nabla\phi(x)\|_\infty}$$

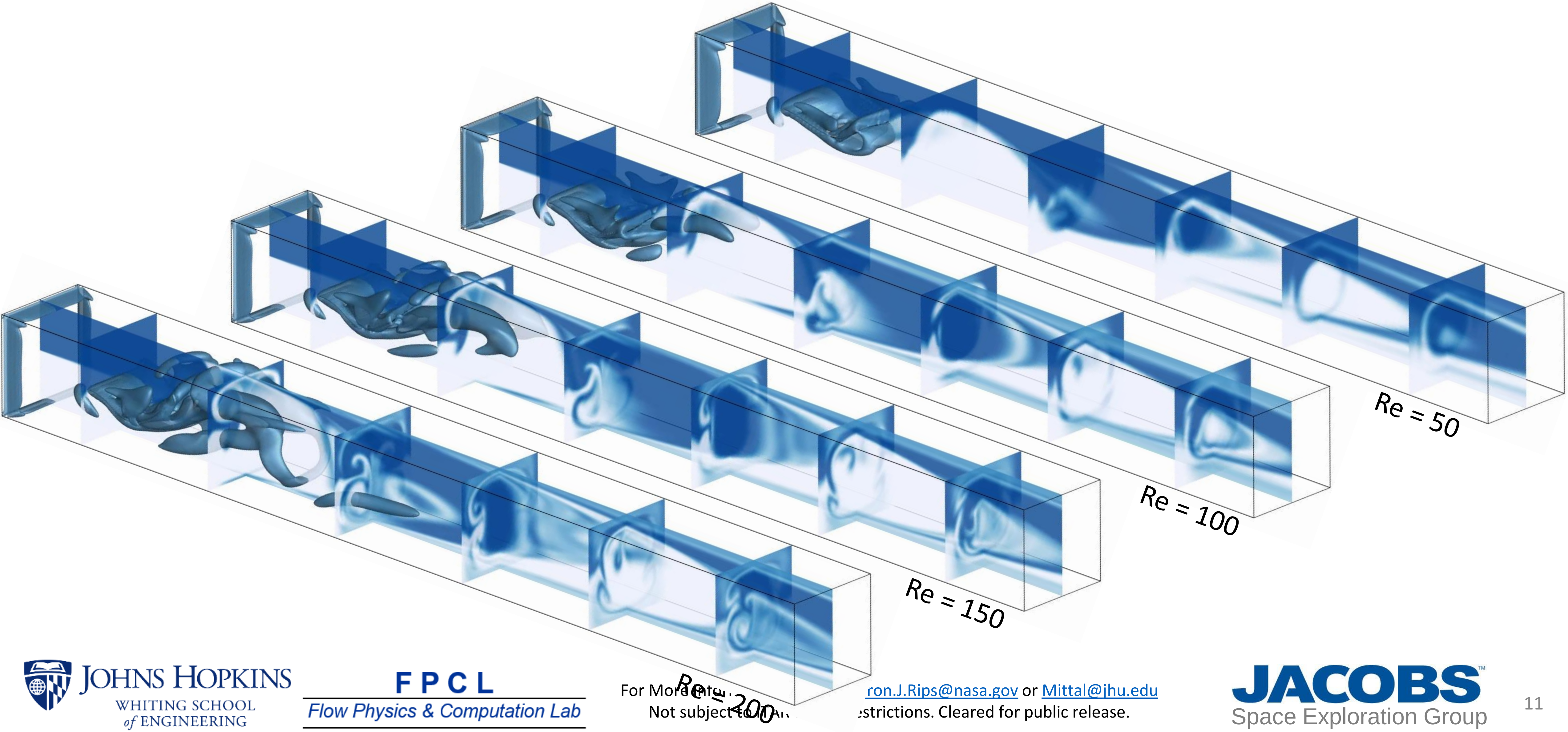
$$I_D(x) = \frac{1}{L^2}\sum_{z=0}^{Z}\sum_{y=0}^{Y}\zeta(x,y,z)$$

Mixing Index (M)

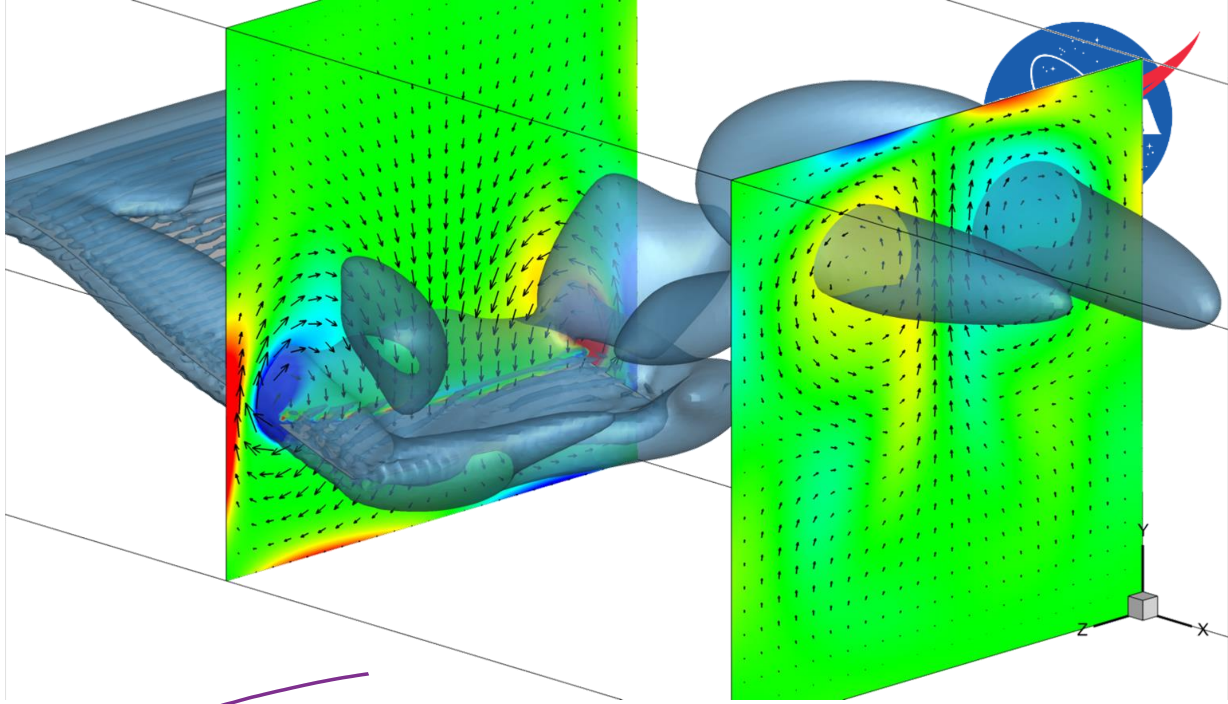
$$\sigma = \sqrt{\frac{1}{L^2}\int_0^Z \int_0^Y (\phi(x,y,z) - \bar{\phi}_m(x))^2 dy\, dz}$$

$$M = 1 - \sqrt{\frac{\sigma^2}{\sigma_m^2}}$$

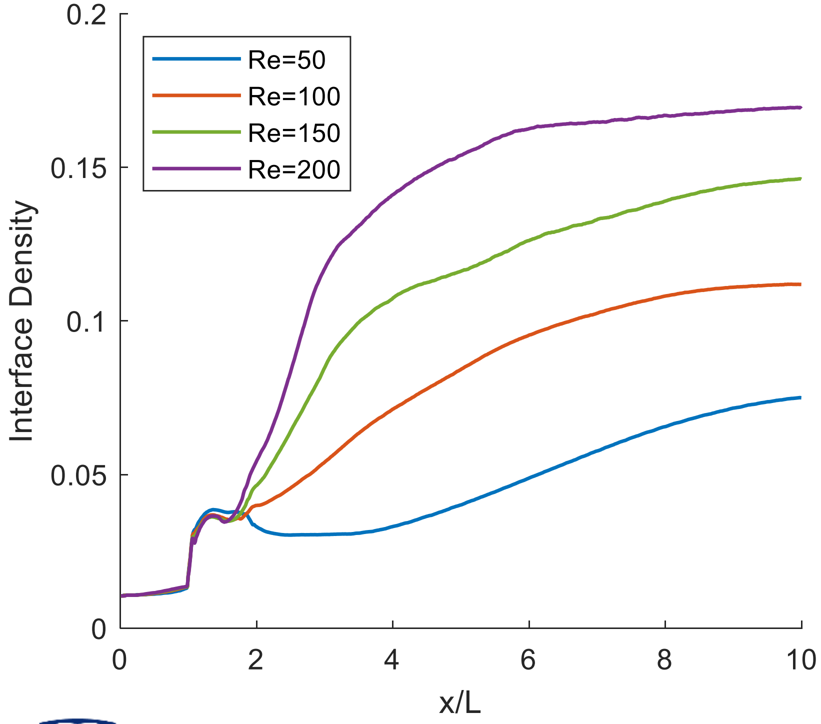
3D Visualizations

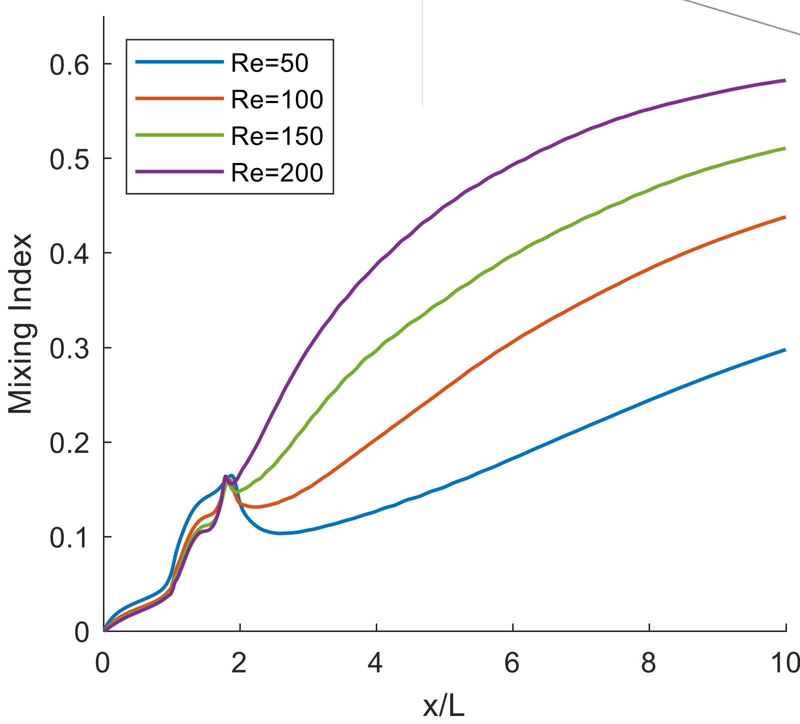


Mixing Mechanism and Performance



Interface Density increase lead Mixing Index improvements





Streamwise vortices are the leading edge vortices on the streamwise edges of the flag

These horseshoe vortices are typical of 3D flapping flags

The confinement aligns the horseshoe in the flow direction, making it more persistent

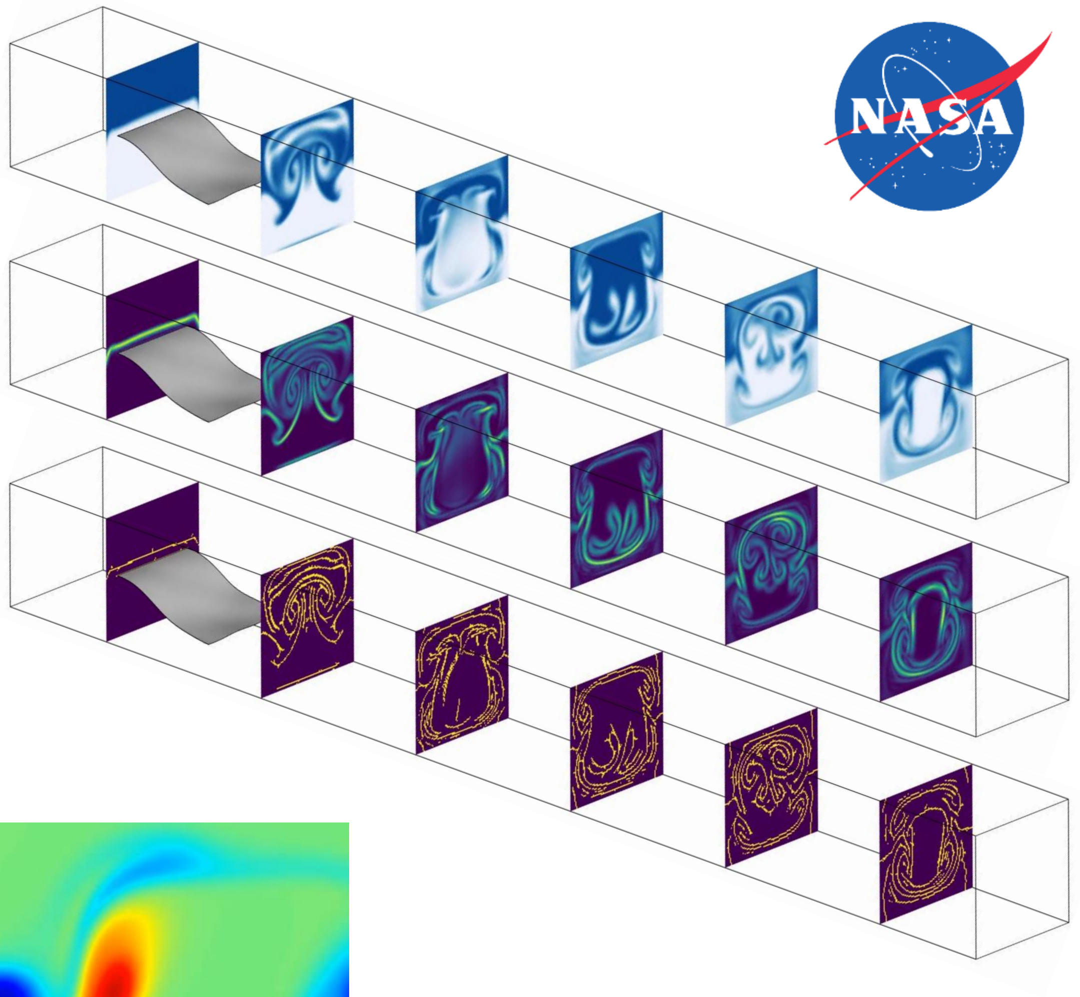
Acknowledgements

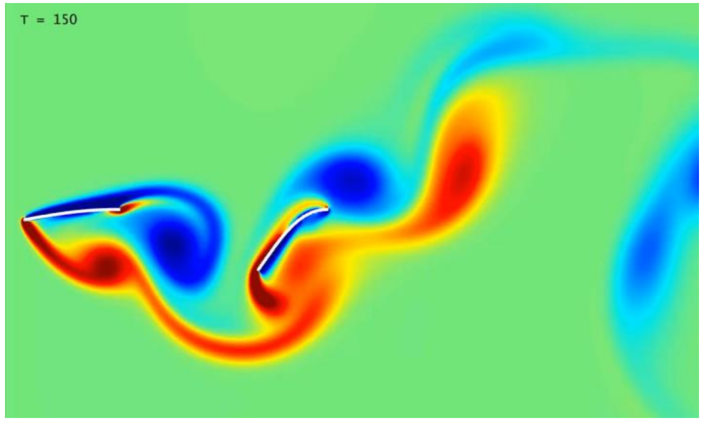
- Sponsors: NSF, EPRI, AFOSR
- JHU engineering community
- Lab mates
- Professors, teachers, mentors
- My advisor Prof. Rajat Mittal

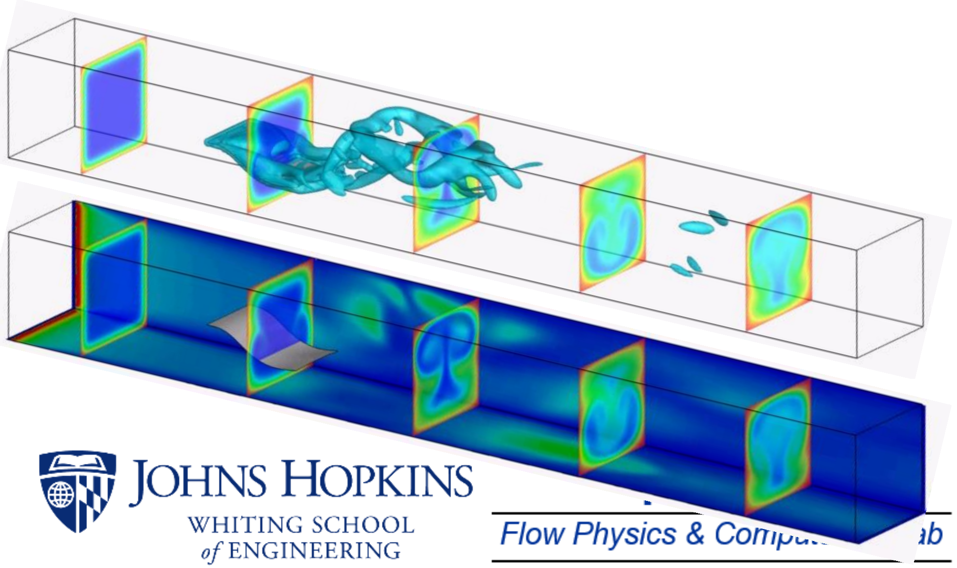
Conclusions

- Flow Induced Flutter can be harnessed for engineering applications
  - Heat Transfer, Mixing, and Energy Harvesting

- Taking advantage of a Passive-Unsteady flow control strategy







Questions?

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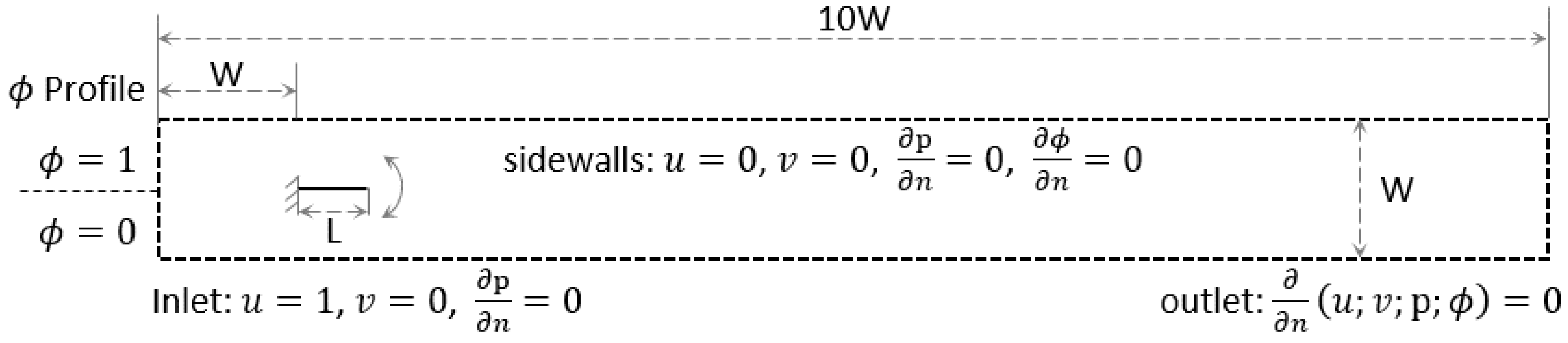
Backup Slides

Mixing Enhancement: 2D Problem Description



- Uniform fluid grid:
  - $dx = dy = 0.016L$
  - 1280x128 points
- Structure grid:
  - $ds = 0.012L$ or 80 points
- Temporal resolution:
  - $dt = 1.0 \times 10^{-4}$
  - 10^6 time steps

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\nabla p + \frac{1}{\mathrm{Re}} \nabla^2 \mathbf{u} + \mathbf{f}$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \frac{1}{\mathrm{Re} \cdot \mathrm{Sc}} \nabla^2 \phi$$

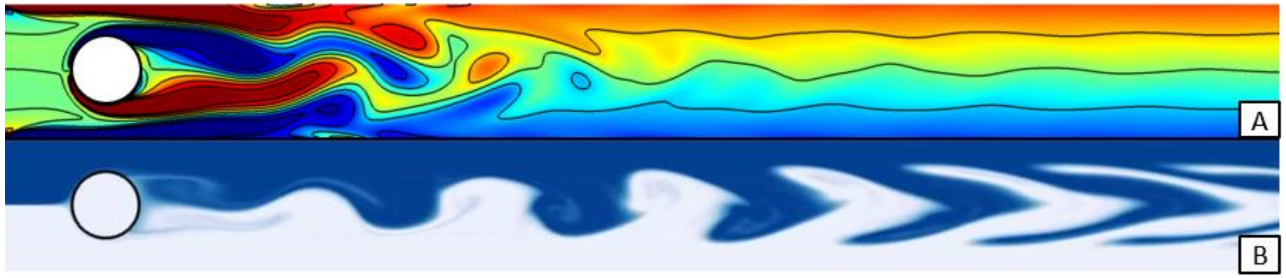
$$\frac{\partial^2 \mathbf{X}}{\partial t^2} = \frac{\partial}{\partial s}\left(\varsigma \frac{\partial \mathbf{X}}{\partial s}\right) - \frac{\partial^2}{\partial s^2}\left(\frac{M^*}{U^{*2}} \frac{\partial \mathbf{X}}{\partial s}\right) - M^* \mathbf{F}$$

$$\frac{\partial \mathbf{X}}{\partial s} \cdot \frac{\partial^2}{\partial s^2}\left(\varsigma \frac{\partial \mathbf{X}}{\partial s}\right) = \frac{1}{2} \frac{\partial^2}{\partial t^2}\left(\frac{\partial \mathbf{X}}{\partial s} \cdot \frac{\partial \mathbf{X}}{\partial s}\right) - \frac{\partial^2 \mathbf{X}}{\partial t \partial s} \cdot \frac{\partial^2 \mathbf{X}}{\partial t \partial s} - \frac{\partial \mathbf{X}}{\partial s} \cdot \frac{\partial}{\partial s}(\mathbf{F})$$

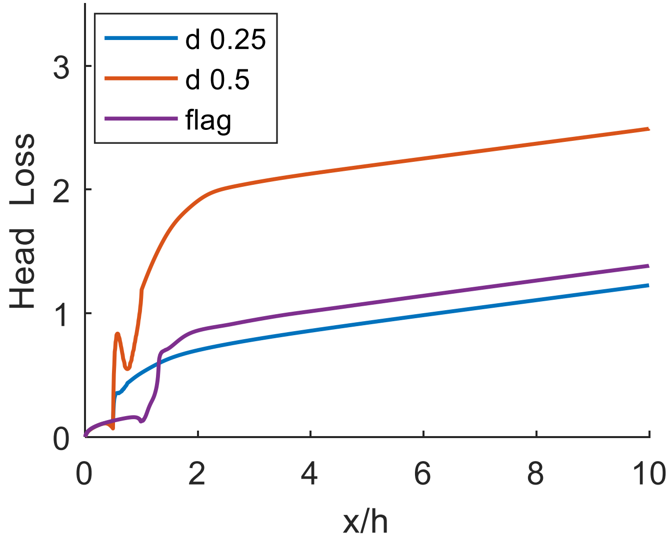
Parametric Sweep

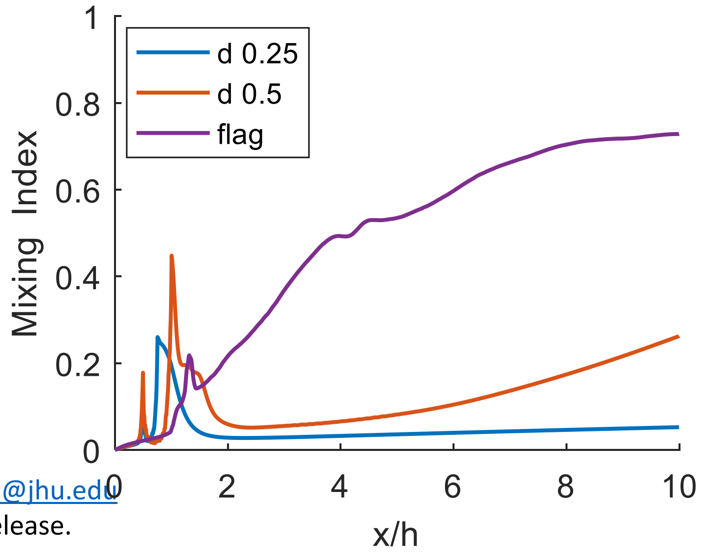
- L=W/2 Re: 25, 37.5, 50, 100, 150, 200
- L=W Re: 15, 20, 25, 50, 100, 150, 200
- L=2W Re: 10, 15, 20, 25
- Sc sweep (L=W/2, Re=200): 1, 10, 100, 1000

Mixing Enhancement: 2D
Bluff Body Mixing

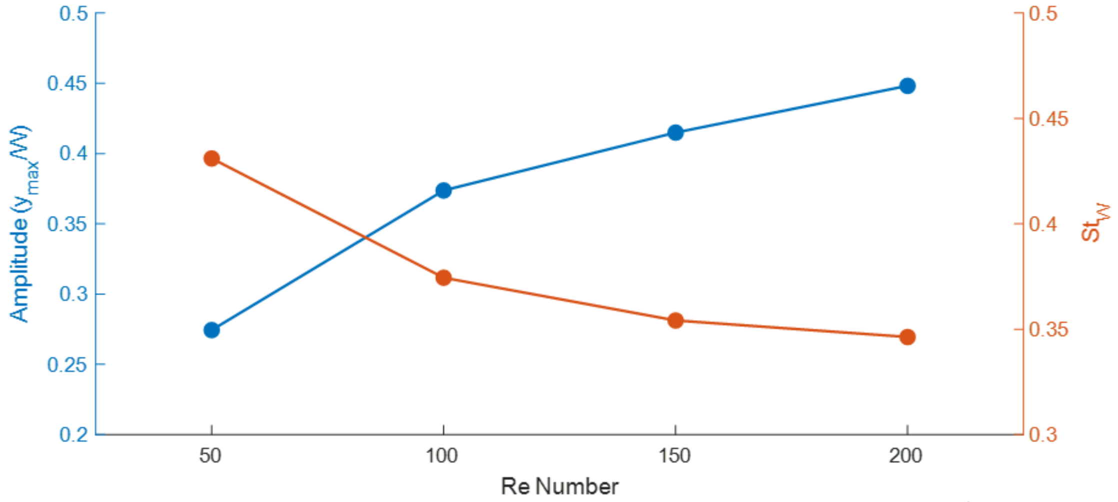


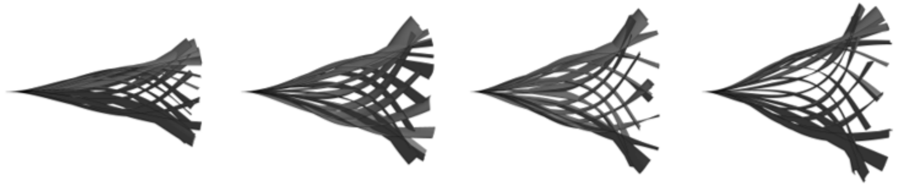
A single flapping membrane is meant as a single unit of a larger system. In which case it is analogous to a single cylinder in a post mixer

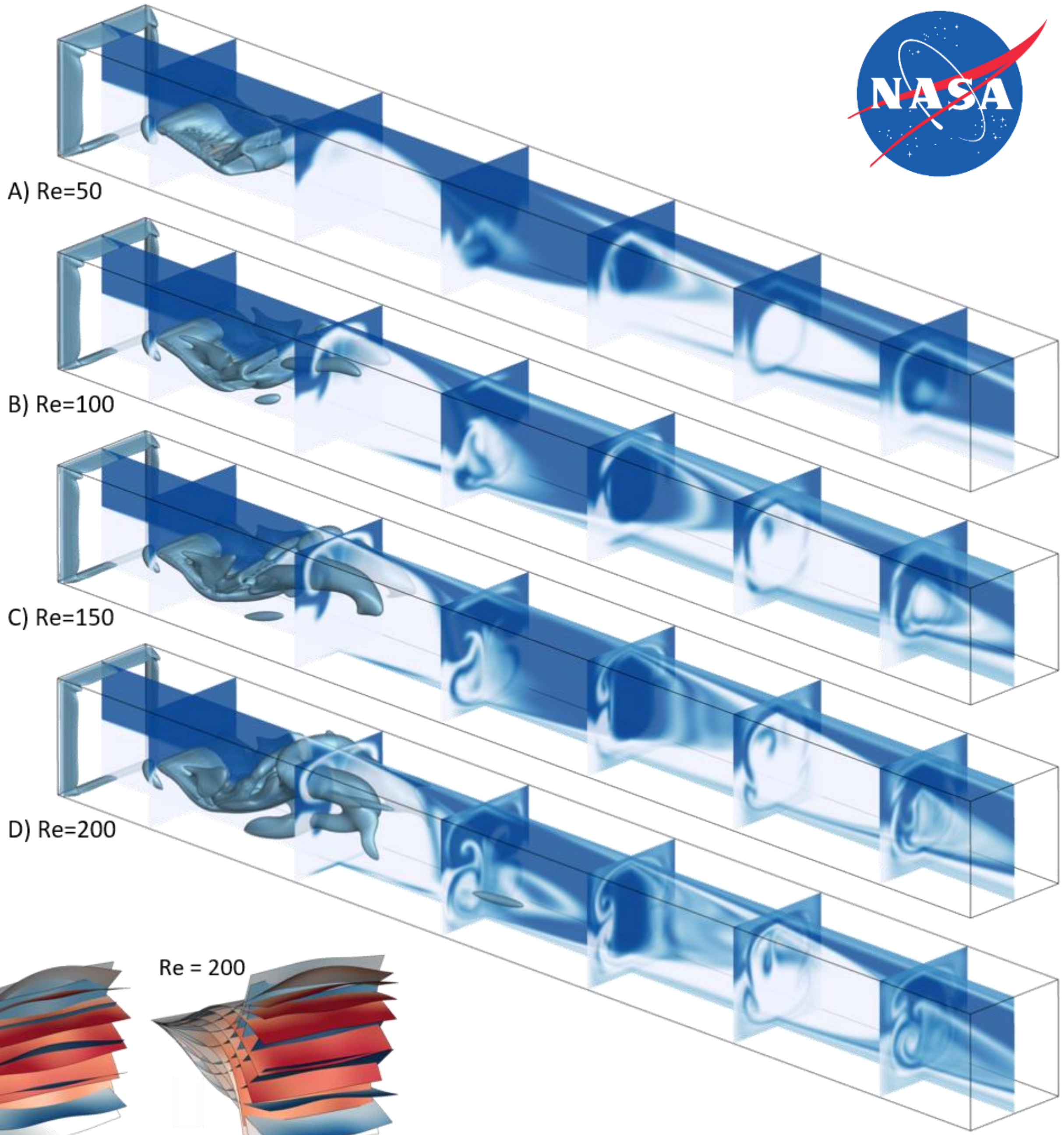


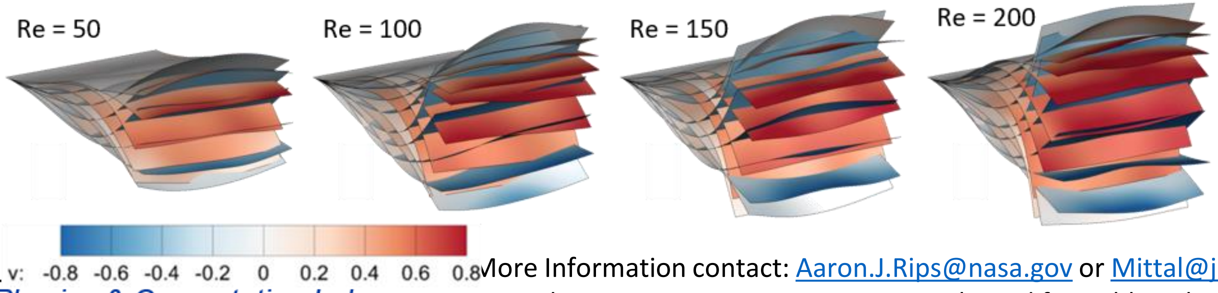


Effect of Reynolds Number









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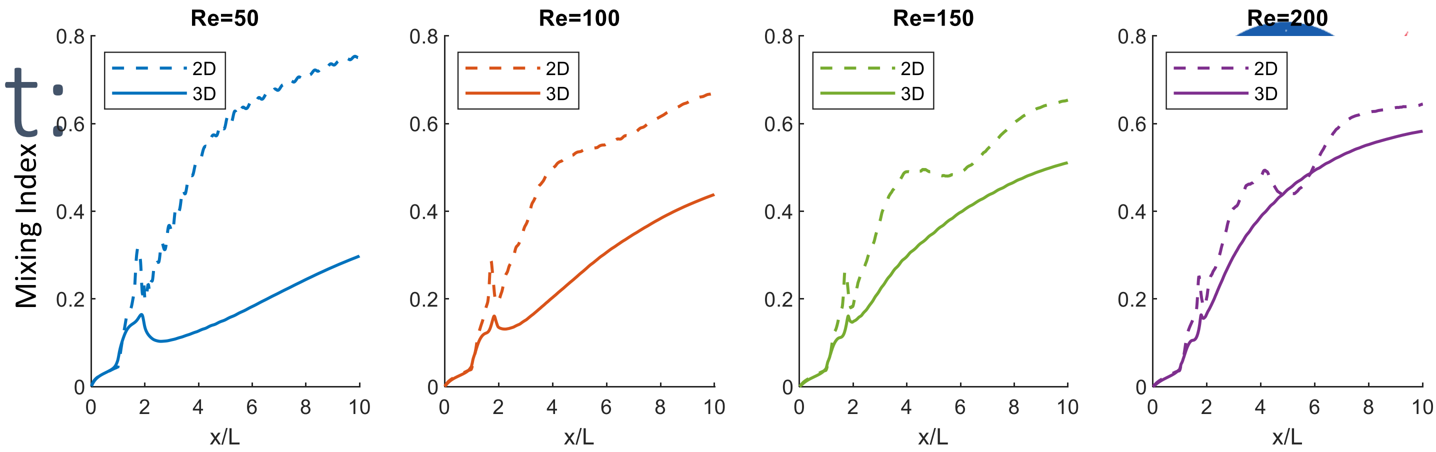
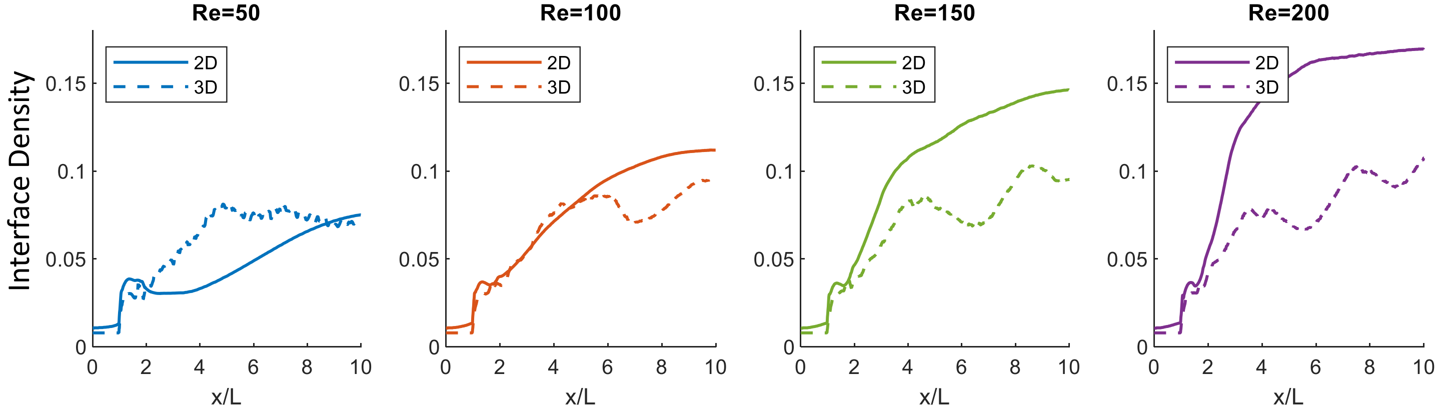
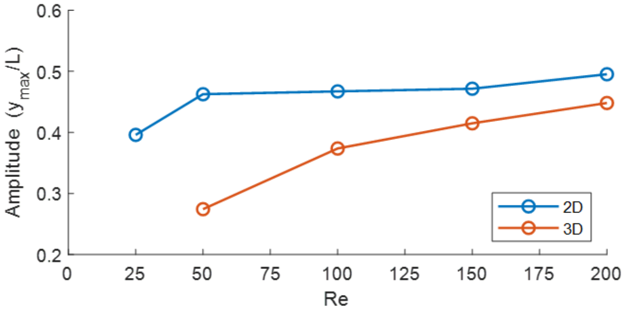
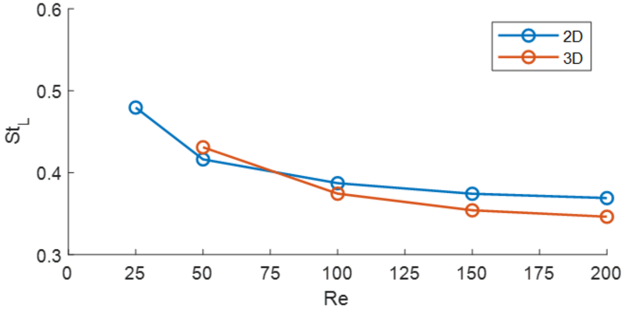
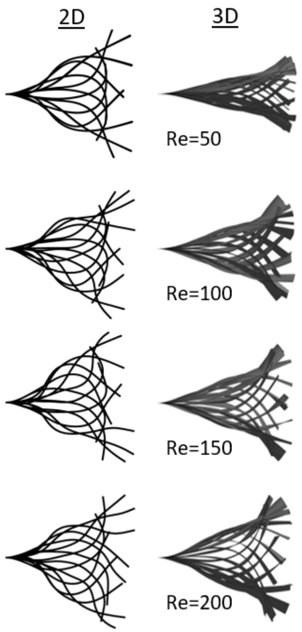
Mixing Enhancement: 2D vs. 3D



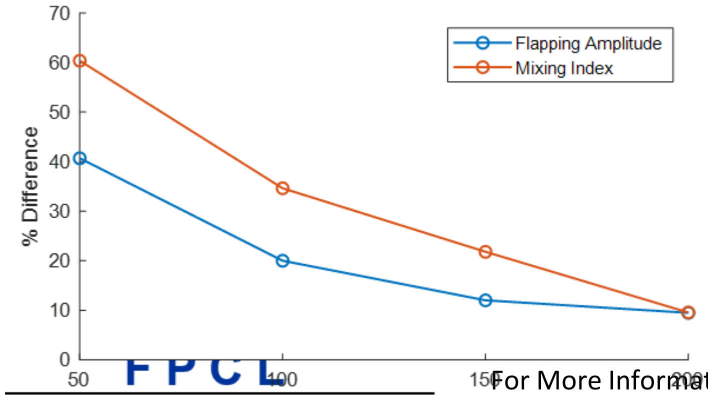


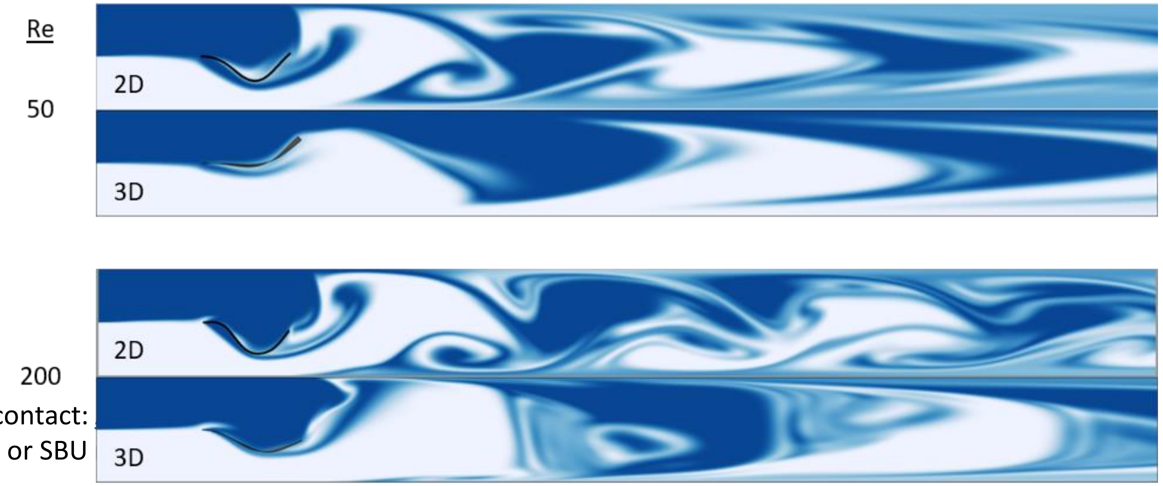






Marginal Correlation between amplitude difference and mixing index difference





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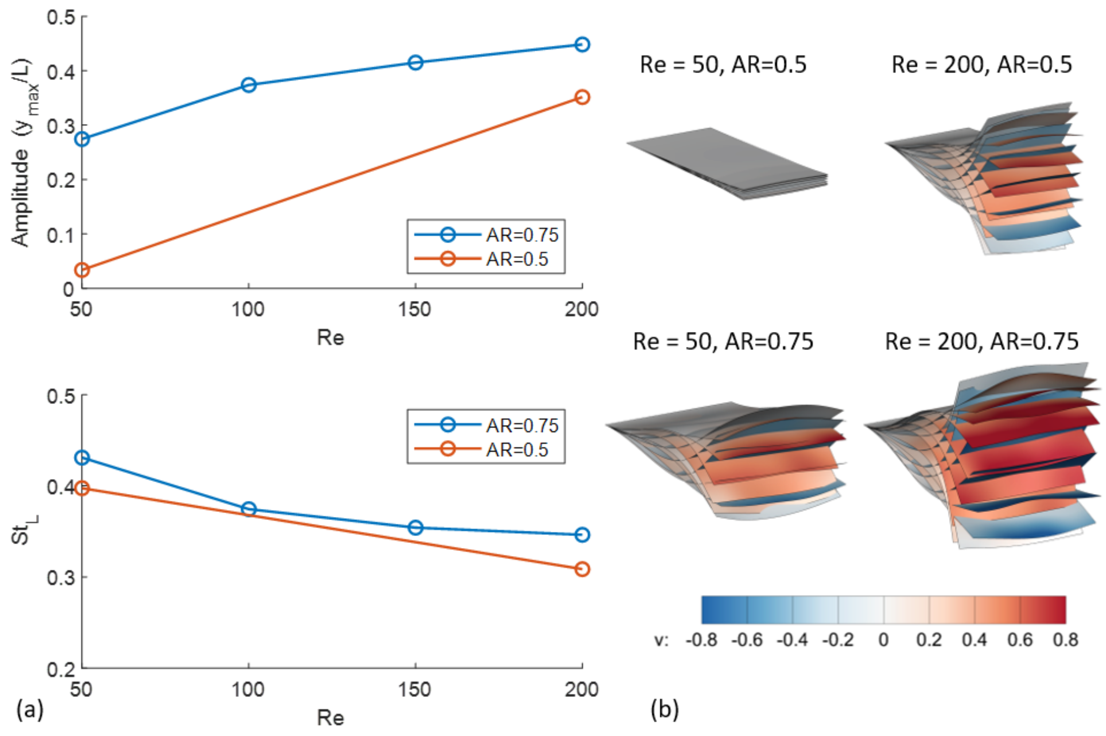
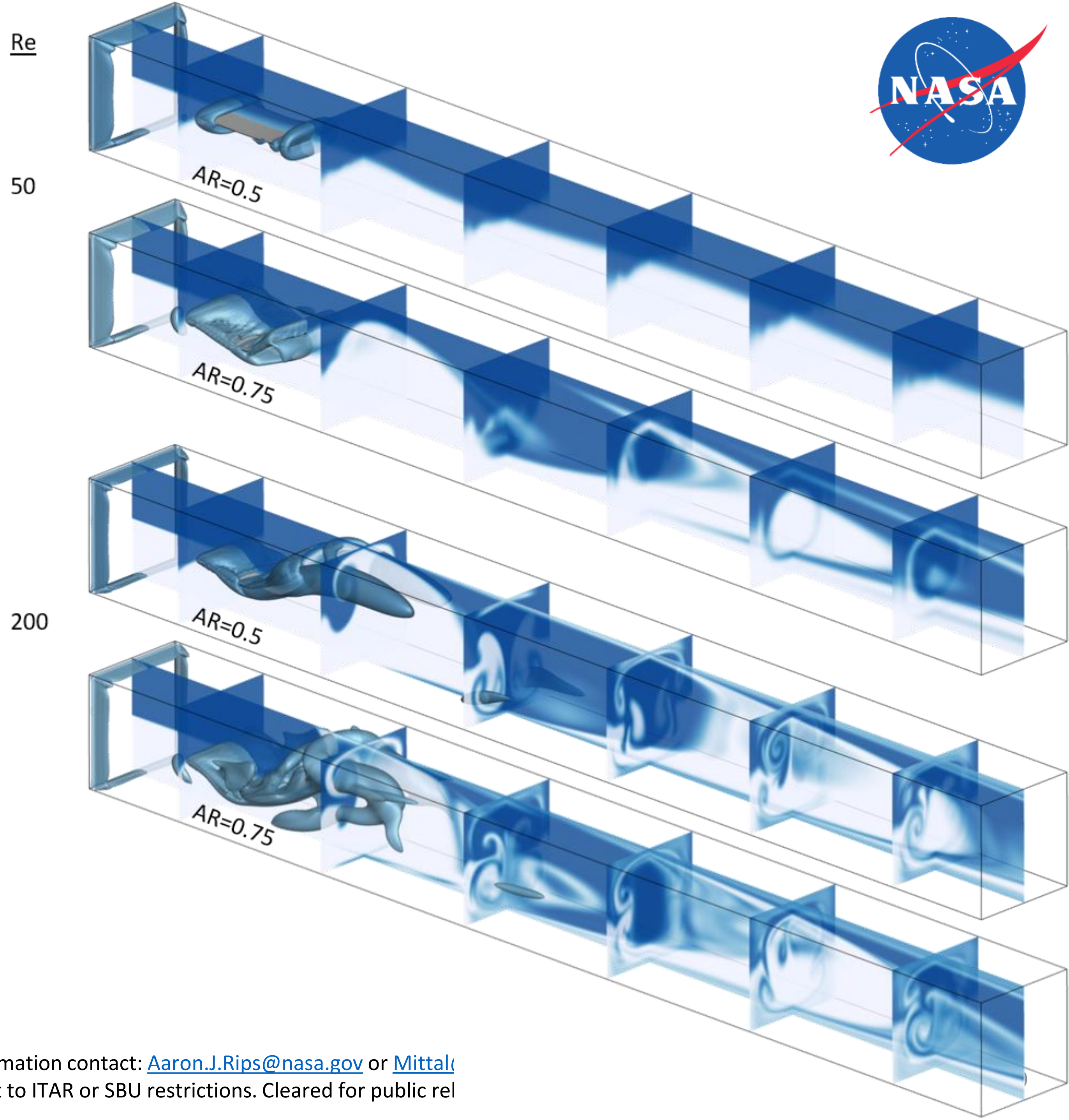
Confinement and Spanwise Gap





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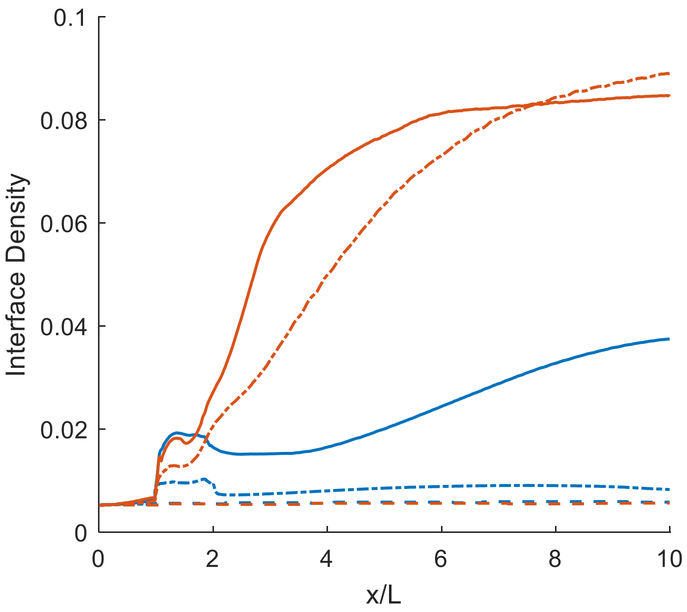

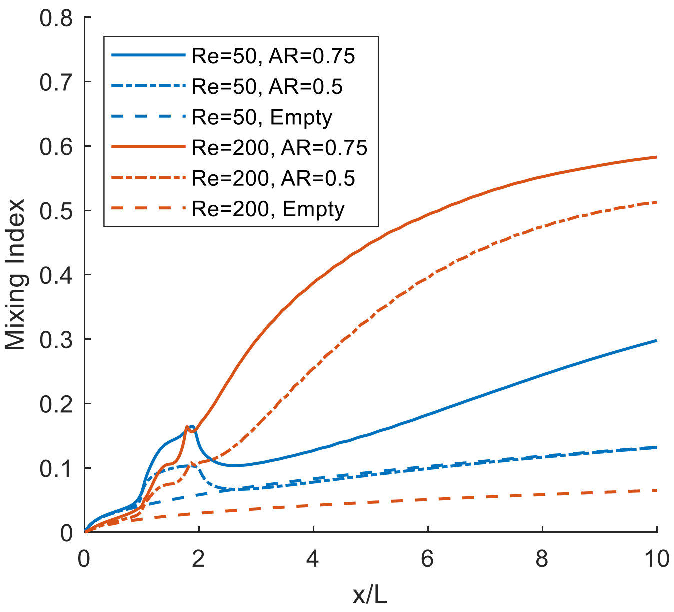

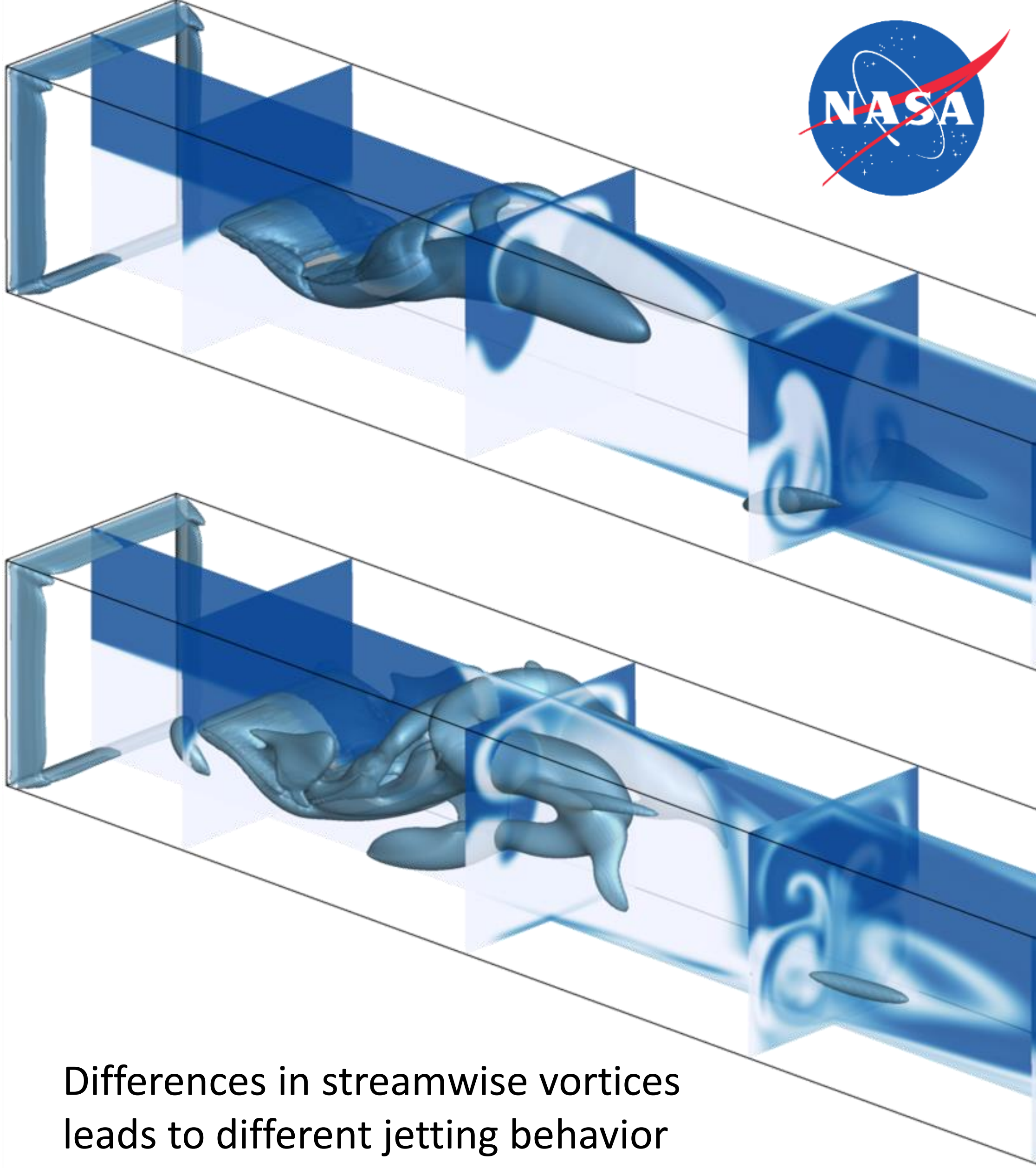

Differences in streamwise vortices leads to different jetting behavior